Estuaries and Coasts
DOI 10.1007/s12237-012-9518-7

Larval Pacific Herring (*Clupea pallasi*) Survival in Suspended Sediment

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Received 17 August 2011 / Revised 4 April 2012 / Accepted 20 May 2012

Abstract Pacific herring early life stages provide good model systems for studying effects of suspended sediments on estuarine organisms To investigate effects on the herring larval stage, we used environmentally relevant particle concentrations for San Francisco Bay (200–400 mg/L of particles <50 μm in size) and exposure times of 16 h in a novel two-pump sediment suspension mesocosm. There were no mortalities during the 16-h suspended sediment incubation Following sediment exposure, larvae were cultured in sediment-free water for up to 10 days during which survival and condition were measured. None were affected by previous sediment treatment Four criteria for larval condition included growth, heart rate, prey capture, and critical swimming velocity. These results provide a framework for implementing regulatory decisions on anthropogenic activities such as dredging.

Keywords Pacific herring · Sediment · Larvae · Estuaries

Introduction

San Francisco Bay is a shallow heavily urbanized estuary (current average depth of <14 m, USGS 2010) with much of the substratum composed of fine silt and clays from anthropogenic input that began over 150 years ago with Sierra Nevada placer mining (Krone 1979, van Geen and Luoma 1999; Schoellhamer 2011) These sediments can become problematic when suspended either through natural (e g , wind) or anthropogenic (e g , dredging activity) disturbances. Reported biological impacts of suspended sediments vary across species and life stages, are dependent on both concentration and duration, and are not always in agreement even within species (Newcombe and MacDonald 1991, Griffin et al. 2009; Wilbur and Clarke 2001) The overriding goal of the current and previous research (Griffin et al 2009) is to provide a scientific basis from which predictions can be made about suspended sediment effects on the viability of early life stages of marine and estuarine organisms using Pacific herring, *Clupea pallasi*, as a model.

Ambient suspended sediment loads vary depending on weather and freshwater input, but range from 50 to 600 mg/L for San Francisco Bay (Ruhl et al. 2001; Ganju et al. 2004; Ruhl and Schoellhamer 2004, McKee et al. 2006). The highest loads of suspended sediments occur during the winter/spring due to increased freshwater flows from local and regional watersheds, and storm-driven mixing within the estuary (Krone 1979, Ingram and DePaolo 1993; Ingram et al 1996; Watters et al. 2004; McKee et al 2006; Schoellhamer 2011). Dredging activity locally adds to these ambient levels and can result in 800- to 1,000-mg/L dredge plumes over a distance of up to 1,000 m depending on dredge type and environmental conditions (Wilber and Clarke 2001). In San Francisco Bay, dredging activity is seasonally and regionally regulated based on potential effects to local species

Pacific herring are a good model system for investigating effects of suspended sediments on different life stages of aquatic organisms Both the adhesive embryonic as well as

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Published online 03 June 2012

planktonic larval life stages occur in estuaries and do so during times of the year when suspended sediment loads are highest (Alderdice and Velsen 1971; Krone 1979; Spratt 1981, Hay 1985; Barnhart 1988, McKee et al. 2006, see also Watters et al. 2004). Previous laboratory research demonstrated that suspended sediments have an impact on embryonic development, but only if 250 mg/L or more of sediment particles is present during the first 2 h after release of eggs into the water (during the formation of the egg/embryo adhesive layer, Griffin et al. 2009). The impact of suspended sediment on hatched larvae after they have left the protection of the chorion has received limited attention. In a number of studies, suspended sediment and associated toxicants have been linked with measures of larval condition, including position in the water column, swimming ability, and prey capture (Brett 1964, 1967, Swenson and Matson 1976, Auld and Schubel 1978, Boehlert and Morgan 1985, Fox et al. 1999; Colby and Hoss 2004; Utne-Palm 2004; reviewed by Wilber and Clarke 2001) To our knowledge, there have been no reports that directly link suspended sediment and survival of herring larvae. The current study shows that larval exposure to suspended sediment during early post-hatch stages does not decrease larval survival, growth, and/or condition.

Materials and Methods

Solutions

Half-strength seawater at 16 practical salinity units (psu) was made by diluting 0.5 μm filtered seawater 1:1 with distilled water. Seawaters were stored at 12°C. Salinity was monitored with a salinometer. Calcium- and magnesium-free (CaMgF) half-strength seawater was made by diluting full-strength CaMgF seawater (Cavanaugh 1956) with equal parts distilled water. CaMgF polyvinyl alcohol (PVA) was prepared by adding 0 25 % PVA to 16 psu CaMgF water and stored at 4°C. All chemicals were obtained from Sigma-Aldrich (St. Louis, MO).

Sediment Storage and Handling

Two sources of suspended sediment were used in the study. Fuller's earth (Sigma-Aldrich) and San Francisco Bay dredged sediment from the Port of Redwood City (US Army Corps of Engineers (USACE), San Francisco, CA) Fuller's earth was stored dry as packaged by the manufacturer. Port of Redwood City sediments were obtained prior to the 2006 reproductive season and were stored in glass-lidded jars (250 ml) at −20°C. The USACE provided both chemical analysis and biological toxicity testing results of the dredged sediment. Three elements (chromium, mercury, and silver) were above San Francisco (SF) Bay background levels; all three were less than 125 % of background (internal report, USACE 2005). Survival of *Rhepoxynius abronius* and *Ampelisca abdita* was greater than or equal to 90 % in the biological toxicity tests (internal report USACE 2005). Fuller's earth and Port of Redwood City sediments were not distinguished experimentally since we previously showed that sediment impact on herring embryos was not a function of sediment source (Griffin et al. 2009)

Sediments with particle sizes of less than 50 μm were obtained by suspension and washing as described by Griffin et al. (2009) except that the final stock concentration was 4 g/L. Briefly, 8 g of Fuller's earth or 12 g of SF Bay sediment was suspended in 1 L of 16-psu seawater at 4°C and stirred vigorously with a magnetic stir bar for 60 min, and the larger particles were allowed to settle for 30 min. The resultant supernatant was decanted and allowed to settle overnight at 4°C. Settled particles were washed twice and gravity filtered twice through Whatman #2 filters, and the concentration of the suspension was determined by obtaining the dry weight measurement of sediment from a 100-ml aliquot. We also used a standard suspended sediment concentration curve based on absorbance at 546 nm in a Biomate spectrophotometer (Thermo Spectronic) of known concentrations of suspended Fuller's earth (Griffin et al. 2009). This standard curve was used to validate dry weight concentration determinations and larval exposure concentrations.

Acquisition of Gametes, Fertilization, and Embryo Culture

Pacific herring were obtained from San Francisco Bay and transported on ice to the Bodega Marine Lab. Ovaries and testes were dissected from gravid animals and kept refrigerated in Petri dishes at 4°C until used (up to 4 days; Yanagimachi et al. 1992). Larvae were obtained through laboratory fertilizations as previously described (Yanagimachi et al. 1992; Griffin et al. 1998, 2009). Fertilizations were conducted in 10×20-cm rectangular PYREX®dishes in which the bases of the dishes served as the substrate for egg attachment. Sperm (10^5 cells/ml) that had been collected from five males were added to 400–500 ml of 16-psu sediment-free seawater, and approximately 500 herring eggs (pooled from five females) were distributed evenly into the dishes in a monolayer and incubated for 2 h. The resultant embryos were washed twice in 16-psu seawater to remove excess sperm and were cultured in a 12°C incubator until hatching (7–12 days). The dishes were monitored, dead embryos removed, and the culture water was changed (100 % exchange) daily.

Larvae were transferred to clean PYREX® dishes within 24 h of hatching Hatching proceeded for 2–3 days, during which time larvae were pooled from the embryo dish in which they had hatched and used in experiments. A 75 % water exchange was conducted daily.

Sediment Treatment Mesocosm

The sediment treatment mesocosm consisted of a square 1.2×1.2×0.6-m-deep container that held four conical sediment treatment tanks, each of which contained three larval chambers (Fig. 1). Larval chambers were 2-L Nalgene® graduated beakers (19 cm high, 15 cm inside diameter at the top tapering to 12.7 cm inside diameter at the bottom) from which the bottoms were cut out and replaced with 500-μm Nitex mesh. Chambers were suspended inside conical sediment treatment tanks (maximum volume of 60 L, 62 cm high with an inside diameter of 37 cm) that were filled with 48 L of either suspended sediment or sediment-free water. A two-pump particle suspension and delivery setup with a baffle separating the two pumps insulated larvae from sediment-suspending currents (Fig 2). Sediment was kept in suspension and circulated with a 17-L/min Aqua Clear 50 submersible pump through a PVC T-connector that created two oppositely directed circular currents near and parallel to the bottom of the tank A 1×1-cm^2 plastic grid baffle overlain with ½-cm^2 Vexar mesh was situated above the mixing pump The second submersible pump (Aqua Clear 30), attached to the side of the sediment treatment tank just above the baffle, delivered sediment water to a multiport manifold (M) at the top of the treatment tank that supplied each larval chamber with resuspended sediment water (Fig. 2) Flow rates to larval chambers were adjustable with the manifold, 6 L/min was used for the current study. There was a constant downward flow of water and suspended sediment, entering at the top and exiting through the 500-μm mesh bottom in each larval chamber. A flow rate of 6–7 L/min was determined to be sufficient to maintain particles in suspension, while not adversely affecting larvae (data not shown). The 1.2×1.2×0.6-m-deep tank contained flow-through seawater (11–12°C) for temperature control.

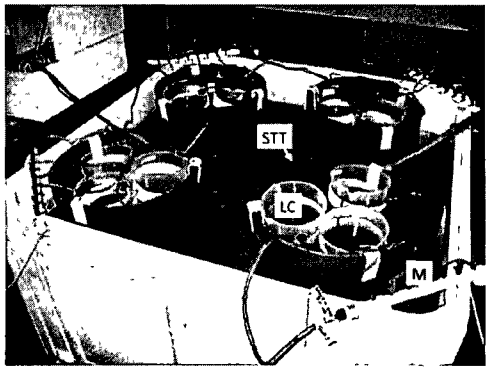

Fig. 1 Sediment treatment system The system consisted of a 1 2× 1 2×0 6-m-deep square tank that was supplied with ambient flow-through seawater for temperature control Four sediment treatment tanks (*STT*) were placed in the system Each treatment tank had three larval test chambers (*LC*) that were supplied with suspended sediment from submersible pumps through an adjustable manifold (*M*)

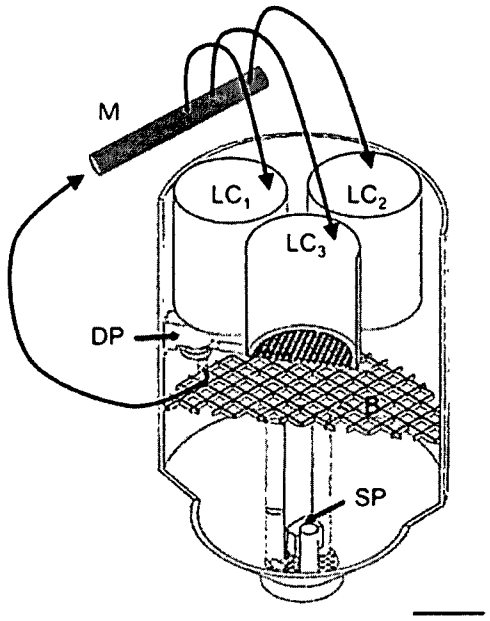

Fig. 2 Sediment treatment tank and water flow scheme The tank is a 60-L conical bottom tank A sediment suspension pump (*SP*) that collects and resuspends settling sediment particles is attached to a plate at the tank bottom A baffle (*B*) that is constructed from a 1×1-cm plastic grid overlain by a ½-cm^2 Vexar mesh is situated 25 cm above the bottom of the tank on PVC pipe legs A sediment delivery pump (*DP*) is attached to the inner wall of the tank above the baffle, but below three larval chambers (*LC*) Larval chambers are 2-L beakers with 500-μm Nitex mesh bottoms that are suspended into the tank at the top of the water column Delivery of suspended sediment to larval chambers comes from the sediment delivery pump that is connected via tubing to a multiport manifold (*M*) that supplies water to the top of each larval chamber via airline tubing (*arrows* leading from the manifold) Adobe Inventor 2010 and PowerPoint 2008 software were used to generate the system drawing *Scale bar*=10 cm

Testing of Sediment Treatment Mesocosm

The ability of the sediment treatment mesocosm to maintain sediment particles in suspension was tested without larvae. Six liters of 4 g/L Fuller's earth was added to 42 L of sediment-free water in the center of a sediment treatment tank. Three-milliliter samples were removed from each of the larval chambers and particle concentrations determined with the Biomate spectrophotometer (see "Sediment Storage and Handling" section). The first sample was collected at 15 min and denoted as time 0 concentration; subsequent samples were collected hourly for 20 h.

System efficiency was less than 100 %. Sediment concentrations within larval chambers initially increased during the first 2 h, then declined, but at no time did the concentration reach 500 mg/L (Fig 3) The 2-h sediment concentrations were highest and therefore were denoted as the starting concentration In test runs, the starting concentration averaged 338.4±11.1 mg/L The decrease in suspended sediment particles through hour 5 was 46 0±13 0 mg/L

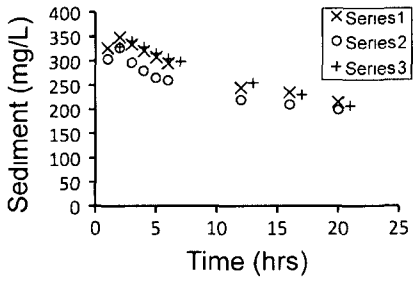

Fig. 3 Suspended sediment levels in the sediment treatment system Six liters of 4 g/L of Fullers earth was added to 42 L of water (expected final concentration of 500 mg/L) and sampled hourly for 20 h Three replicates were conducted in the absence of larvae (*multiplication signs, circles, addition signs*)

(average rate of loss was 15 mg/L/h). Over the next 7 h (hours 5–12), the loss totaled 52.2±7.5 (loss of 5.7 mg/L/h) and from hours 12–20 totaled 32 5±13.8 (average of 4.1± 1.7 mg/L). The ending suspended sediment concentration was 207.58±8 2 mg/L at hour 20 (61 34±0.55 % of the starting concentration). Sediment particles that settled out of suspension accumulated in two areas of the system: around the bottom perimeter inside the larval chambers where the Nitex mesh was silicone glued to the chamber and on the walls of treatment tanks at or near the bottom. Collected sediment did not impact the Nitex mesh or the flow of water through the chambers.

Suspended sediment concentrations in the 16-h experiments with larvae showed similar declines. In two of the experiments using Fuller's earth, the final concentrations were 316 and 281 mg/L, respectively In the two experiments with SF Bay sediment, the ending concentrations were 195 and 366 mg/L.

Larval Sediment Treatment

The sediment treatment mesocosm was temperature equilibrated prior to each larval experiment. Sediment-free water (42 L) was added to the control and sediment treatment tanks 24 h prior to an experiment. Five hours prior to each experiment, 6 L of stock suspended sediment (4 g/L) was added as described in the "Testing of Sediment Treatment Mesocosm" section. After 2 h, samples of water were removed from each of the three larval chambers by pipette, and the sediment concentrations were measured in the larval chambers and averaged as the beginning concentration in the treatment tank. Samples of water were also removed at experiment termination and denoted as ending suspended sediment concentration.

Larvae were transferred from PYREX® culture dishes to mesocosm larval chambers (contents of one dish into each chamber, 300–500 larvae per chamber, depending on the hatch rate) Larvae were exposed to suspended sediments in the mesocosm for 16 h (time of exposure based on San Francisco Bay semidiurnal tidal cycles) after which larvae were transferred to sediment-free culture dishes. The larvae were cultured for 10 days at 12°C without feeding to monitor growth and survival. Mortalities were removed daily.

Aliquots of live larvae (ten per treatment) were removed, sedated in 100 μg/ml MS222 (a fish anesthetic), and photographed using a Nikon AZ100 stereo zoom microscope controlled by NIS Elements Imaging Software 3.10. Larval length was measured with ImageJ software (National Institutes of Health) and calibrated against collected images of a 2-mm stage micrometer.

Heart Rate

Heart rate was determined from AVI image files of larvae. Individual larvae (ten per treatment) were transferred by disposable pipette to welled slides containing 100 μg/ml MS222, the slides were mounted on a temperature-controlled slide holder attached to a Nikon AZ100 stereo zoom microscope, and 10-s AVI images were collected through a Photometrics CoolSNAP HQ^2 camera using NIS Elements Imaging Software 3.10. The number of heartbeats in each 10-s segment was translated into beats per minute

Prey Capture Test

The ability of larvae to capture prey was tested following sediment exposure. Ten to 20 larvae were transferred to 100-ml circular glass dishes containing 16-psu seawater. Rotifers (1,500–2,000) were added and co-incubated with the larvae for 4 h at 13°C, in ambient light. After 4 h, larvae were sedated with MS222 briefly, and digital images of larvae were captured using dark-field optics on the Nikon AZ100 stereo zoom microscope Images of larvae were later scored for the number of rotifers in each larva's digestive tract

Critical Swimming Test

The ability of larvae to withstand a current was quantitatively tested with the incremental velocity (or increased velocity) test (Brett 1964, 1967). During the incremental velocity tests, the larvae are forced to swim against a current that is increased in steps until exhaustion occurs and the fish are unable to maintain position; this is the fatigue or critical swimming speed (U_{crit}). Based upon recent larval swimming reports (Bellwood and Fisher 2001; Fisher 2005) and preliminary tests run on herring in our laboratory, 3-min time intervals were selected and used between steps or velocity increments (t_i) The method to determine the critical swimming speed followed the procedure and formula developed by Brett (1964, 1967) and used by Fisher (2005) and Bellwood and Fisher (2001).

The system consisted of a tubular flow-through larval chamber for determining U_{crit}, a rectangular cooling chamber for temperature control, cool LED illumination, and a computer-controlled black and white digital CCD camera. The tubular flow-through larval chamber was a continuous flow-through system with flow controlled by a peristaltic pump that pushed water into the inlet end and pulled water from the outlet end Temperature was maintained at 12±0.5°C within the tubular larval chamber Incremental velocity changes in the larval chamber were achieved with a Masterflex speed controller that was connected to the peristaltic pump. Velocity was calculated by measuring the time it took to fill a 100-ml graduated cylinder for each pump step

For each critical swimming test, three to five larvae were acclimated in the larval chamber for 10 min without a current followed by 3 min with the current at step 1 (0.75 cm/s) before tests were started Velocity was then increased in 2.25-cm/s steps at 3-min intervals until fatigue occurred If a larva could not extend one body length off the downstream barrier for 1 min, it was considered fatigued Only data from larvae that had no visible morphological abnormalities and were able to recover from fatigue (swim in the absence of current at the end of the test) were used.

Statistical Analysis

Data were compiled in Excel spreadsheets (Microsoft Corporation) and analyzed using Excel and SYSTAT (SYSTAT Software, Inc) software. Unless otherwise identified, data are presented as means±standard error (minimum n=3). Student's t tests were used to determine the significance of differences between sediment-treated larvae and controls. A grand mean±standard error of four experiments was utilized to determine overall mortality and larval length differences between control and sediment-treated larvae

Results

Larval Survival and Growth After Sediment Treatment

Pacific herring larvae survived 16 h in 200- to 400-mg/L suspended sediment Furthermore, 10-day larval survival following transfer to and culture in sediment-free water was not reduced by the 16-h sediment treatment. Ten-day survival of sediment-treated larvae in four experiments (each run in triplicate with 300–500 larvae/replicate) averaged 85 4 % while control survival was 85.8 %. The average mortality rates ranged from 0 6 to 2 9 % per day, overall average of 1.46 %, for sediment-treated larvae, while control mortality ranged from 0.8 to 1.9 % per day, with an overall average of 1 42 % The grand mean for cumulative mortality on day 10 was 14 61±1 35 % for sediment-treated larvae compared to 14 16±1.1 % for control larvae (P=0.901, Fig 4).

Cumulative larval mortality in two of the experiments (experiment 1 with Fuller's earth and experiment 4 with SF Bay sediment) was less than 10 % on day 10 and was remarkably similar to controls (Table 1) In experiment 2 (SF Bay sediment), overall mortality appeared higher for control larvae (28 07±5.6 % for controls and 14.26±4.2 % for SF Bay sediment). In experiment 3 (Fuller's earth), mortality appeared higher for sediment-treated larvae (30.77±8.02 % for Fullers earth and 15 2±7 19 for controls) However, there was no significant difference between controls and sediment treatments in either experiment 2 or 3 (P=0.076 and P=0 084, respectively)

Larval Condition

Four measures of larval condition, growth, heart rate, prey capture, and larval critical swimming speed (U_{crit}) mirrored survival and growth. Larval length also was not affected by sediment treatment Variability occurred across experiments but was not correlated with sediment treatment The overriding trend in growth over the 10-day post-sediment treatment culture was that larvae continued to increase in length for the first 3–4 days after which average length did not change (Fig. 5).

There was no difference in heart rate between sediment-exposed and control larvae Heart rate (beats per minute) on the day after sediment exposure averaged 170.4±12.7 for sediment-treated larvae and 165.6±8.1 beats for controls. Two days later, heart rate had decreased to 147.6±8 6 and 144.6±12.8, respectively (P>0.05).

Eighty sediment-treated larvae captured an average of 5.79+1.73 rotifers over 4 h, while control larvae (87)

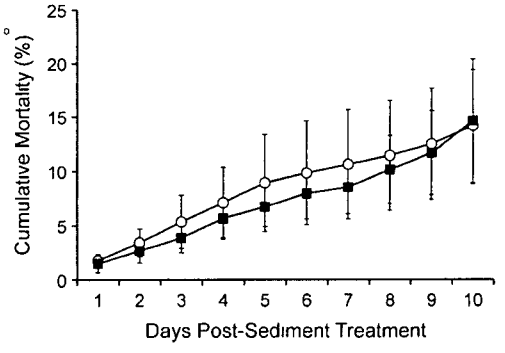

Fig. 4 Grand mean of cumulative mortality Average mortality of four experiments was used to develop a grand mean Cumulative mortality through day 10 for sediment treatment (*black squares*) and controls (*white circles*) was not significantly different Values represent averages±SE (P=0 901) of four experiments that were each conducted in triplicate

Table 1 Cumulative mortality of Pacific herring larvae after the 16-h suspended sediment exposure

Experiment	Sediment (%±SE)	Control (%±SE)	*P* value
1	8 73±1 97 (276[a])	9 81±5 23 (465[a])	0 80
2	14 26±2 42 (370[a])	28 07±2 34 (276[a])	0 076
3	30 87±4 63 (271[a])	15 2±4 15 (246[a])	0 084
4	4 58±1 14 (390[a])	3 56±138 (429[a])	0 073

P=results of Student's *t* test

[a] Average number of larvae at experiment start in each of three replicates

consumed 7.0+2 16 ($P>0.05$) In addition, the percentage of larvae that consumed prey did not vary between sediment-treated larva and controls (39 3±23.24 % of treated larvae compared to 40.99±21 57 % in controls; $P>0.05$).

Critical swimming speed (U_{crit}) ranged from 6.32 to 12 28 cm/s and varied between experiments, but overall was not dependent on whether larvae were treated with suspended sediment For 10 of 12 trials (three to five larvae per trial), there was no significant difference between sediment-treated larvae and controls ($P>0$ 05). In one trial, there was a significant difference where control larvae exhibited higher U_{crit} than did sediment-treated larvae. It was noted that during the acclimation period, the sediment-exposed larvae were not very active (maximum U_{crit} was 4.43 cm/s), but did not seem injured. In one other trial, U_{crit} was higher in the sediment-treated larvae ($P=0.018$)

Discussion

Early post-hatch Pacific herring larvae survived suspended sediment loads in the range of 195 to 366 mg/L for 16 h without observable effects on growth or condition Sediment

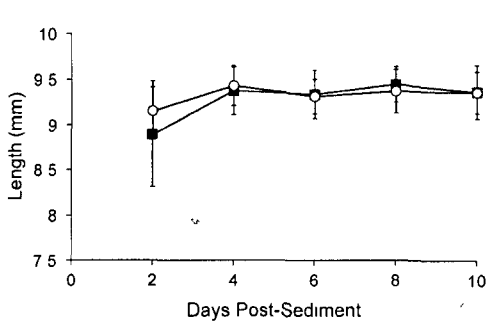

Fig. 5 Grand mean of larval length Larvae from the experiments depicted in Fig 4 were sampled during the 10-day post-sediment culture, and standard length was determined The grand means of sediment-treated (*black squares*) and control (*white circles*) larvae from the four experiments were not significantly different Values represent average±standard deviation ($P_{day\ 10}>0$ 05)

concentration and duration of exposure attempted to address a reasonable worst-case scenario that Pacific herring larvae might encounter as a result of the natural input of suspended sediments or from anthropogenic disturbance of resident sediments from, for example, dredging or other shallow water disturbance activities. Although San Francisco Bay suspended sediment concentrations can reach 600 mg/L (rarely 1,000 mg/L), they are more likely to peak from 200 mg/L to a maximum of 400 mg/L under the most adverse conditions (Ruhl et al. 2001; Ganju et al. 2004; Ruhl and Schoellhamer 2004, McKee et al. 2006; Schoellhamer 2011) For this reason, we chose 200–400 mg/L as our sediment concentrations. The sediment exposure time (16 h) and the slow decrease in sediment concentration over time reflected what might be expected during a localized increase in sediment load that could be expected to decrease with diurnal tidal current direction change and hysteresis (Kostaschuk et al. 1989, West and Sangodoyin 1991; Wilber and Clarke 2001). The current results add to those in a previous study that reported that 2-day post-hatch larvae were not affected by a 2-h exposure to 250 mg/L suspended sediment (Griffin et al. 2009).

There was larval mortality during the 10 days of post-sediment larval culture, but rates were low and not significantly different between sediment-treated and control larvae. The rates of 1 46 % mortality per day in sediment-treated and 1.42 % in control larvae were similar to those previously observed in laboratory larval cultures of <1 5 % per day (Griffin et al. 2004). Post-treatment static culture undoubtedly induced a low-level stress, as evidenced by daily mortalities, and thus, survival was a sensitive measure of whether sediment treatment could additionally stress larvae. Multiple stressors can have added or synergistic impacts (Landis et al. 2004; Landis 2010), so if sediment treatment had a lasting impact, post-treatment mortality rates should have been elevated.

Four measures of larval condition, growth, heart rate, critical swimming speed, and prey capture showed no significant effect. Growth rates for both sediment-exposed larvae and controls initially agreed with previously published daily values of about 2 mm per day length increase (Erlich et al. 1976, McGurk 1984) After day 4, the average larval length did not change; this was not unexpected since larvae were not fed in the static cultures. Heart rate was included as a parameter because it is a measure of overall physiological condition and development. Normal heart rate is known to be reduced by stresses such as salinity stress, hypoxia, and toxicants (Holliday and Blaxter 1960; Middaugh et al. 1998, Vines et al 2000, Pelster et al. 2003). Critical swimming speed is a measure of larval strength, stamina, and development Since visual predation involves prey encounter, detection, pursuit, fixation, attack, and capture, critical swimming speed and prey capture are

linked (Hunter 1981; Utne-Palm 2004) Thus, prey capture was used as the final measure of condition, it reflects overall physiological condition and development since larvae must have developed the morphological ability to feed as well as acquired the swimming ability to capture prey

Suspended sediments can affect organisms in both the water column and on the benthos. Pacific herring embryos and larvae provide two sensitive life stages that can be used to assess sediment load effects in both habitats using one species. There remain, however, significant gaps in knowledge that if addressed could enhance the value of Pacific herring as a test species. One concerns the ability of larvae to swim and capture prey while in the presence of suspended sediments Another involves whether or not previous sediment exposure alters this ability Especially pertinent to Pacific herring is the question of whether larvae derived from eggs treated with suspended sediment during the first 2 h after eggs contact water (which has previously been shown to affect development, Griffin et al. 2009) are more or less capable of tolerating suspended sediments as larvae. The possibility that this might constitute additional stress should be examined. It would also be useful to determine if other species are impacted similarly to herring. It is possible that herring have adapted to high sediment loads as a result of their spawning behavior, i e., during winter months in bays and estuaries when sediment loads are higher. Lastly, in order to determine environmental relevance, field studies that ground-truth the laboratory studies should be conducted. For example, does increased egg aggregation occur in San Francisco Bay when suspended sediment loads are elevated during spawning? Is subsequent larval hatch affected? Are larval survival, growth, and condition affected when these larvae from natural spawns are subjected to suspended sediments? The answers to these questions would provide guidelines for maintaining viable waterways while at the same time protecting ecologically and commercially important resources

Acknowledgments The research was funded through the San Francisco Bay LTMS Environmental Windows Science Work Group by the US Army Corps of Engineers (USACE) San Francisco under contract W912P7-08- P-0077 and W62A2B=8217-0648 We thank Dr William Brostoff and Peter LaCivita, USACE, for consultation and oversight during the project The Larval Sediment Treatment System was designed, constructed, and maintained by Karl Menard, Joe Newman, and the Bodega Marine Laboratory Aquatic Resources Group The Port of Redwood City dredged sediment was supplied for a previous project, originally by Charles Anderson, USACE Toxicity testing information for Port of Redwood City sediment was provided by Michael Donnely and Neil Hedgecock, USACE Ryan Watanabe of the California Department of Fish and Game provided ripe herring from their adult surveys We thank Dr Vic Chow and Suzy Jackson for their assistance with statistical analyses, as well as editorial input This publication is a contribution of the Bodega Marine Laboratory, University of California, Davis

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